Cryogenic Amplifier Based Receivers at Submillimeter Wavelengths

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***Abstract*—The operating frequency of InP high electron mobility transistor (HEMT) based amplifiers has moved well in the submillimeter-wave frequencies over the last couple of years. Working amplifiers with usable gain in waveguide packages has been reported beyond 700 GHz. When cooled cryogenically, they have shown substantial improvement in their noise temperature. This has opened up the real possibility of cryogenic amplifier based heterodyne receivers at submillimeter wavelengths for ground-based, air-borne, and space-based instruments for astrophysics, planetary, and Earth science applications. This paper provides an overview of the science applications at submillimeter wavelengths that will benefit from this technology. It also describes the current state of the InP HEMT based cryogenic amplifier receivers at submillimeter wavelengths.**

I. Introduction

THE scientific importance of high-resolution spectroscopic observations at submillimeter wavelengths is widely recognized by the international scientific community. This importance is underscored by the key role of heterodyne spectrometers in the ESA cornerstone Herschel Space Observatory, NASA's Microwave Limb Sounder (MLS) instrument on Earth Observation System (EOS) Aura satellite, NASA's Microwave Instrument on the Rosetta Orbiter (MIRO), as well as the ground-based Atacama Large Millimeter Array (ALMA), and airborne Stratospheric Observatory for Infrared Astronomy (SOFIA).

Star formation and key phases of galaxy evolution occur in regions enshrouded by dust that obscures them at infrared and optical wavelengths, while the temperature range of the interstellar medium of ten to a few thousand Kelvin in these regions excites a wealth of submillimeter-wave spectral lines. With high-resolution spectroscopy, resolved line profiles reveal the dynamics of star formation, directly revealing details of turbulence, outflows, and core collapse.

Analysis of the chemical composition of various planetary atmospheres such as Mars, Venus, Jupiter, Europa, and Titan is one of the key science objectives of future planetary missions. High resolution heterodyne spectrometers allow a large number of chemical species in the atmospheres of Mars and Titan to be detected at concentrations below a part per billion, and their location to be precisely pinpointed in latitude, longitude, and in altitude. Moreover, the radiometers at these frequencies allow determination of the nature and composition of cometary and planetary surfaces such as those of Mars, Europa, and Titan by measuring the polarization-sensitive thermal emission from the dielectric surfaces.

Spectroscopic measurements of O_3, CO, CH_2O, SO_2, and NO_2 (all has spectroscopic signatures in the submillimeter-wave band) in our own atmosphere is a priority for atmospheric scientists because the intercontinental transport of air pollution is most efficient in the troposphere. On planet Earth, clouds play a crucial role for the climate. They are also a major source of uncertainty in climate predictions. Particularly large uncertainties are associated with those clouds that consist partly or entirely of ice particles. Urgently needed global data on ice clouds, particularly on the so far poorly characterized 'essential climate variable' ice water path (IWP) and on the characteristic cloud ice particle size. Therefore, low-noise, low-mass, low-power, and compact heterodyne receivers for spectroscopy and radiometry are highly desirable at these frequencies.

Traditionally, cryogenically cooled superconductor-insulator-superconductor (SIS) and hot electron bolometer (HEB) mixers and Schottky diode-based receivers have been used for these applications as there were no amplifiers available at the submillimeter wavelengths. However, the availability of indium phosphide (InP) high electron mobility transistor (HEMT) based amplifiers and mixers [1] would change all that. Low noise amplifiers with substantial gain at the front-end may reduce the noise contribution from mixers and IF amplifiers, and power amplification could significantly improve LO efficiencies. Moreover, HEMT based technology provides a great opportunity of high level of integration of various front-end components on a single chip. This is very attractive to future submillimeter instruments where multi-pixel receivers are of high priority. HEMT amplifiers and mixers cooled to 20 K provide a significant improvement in their noise performance compared to receivers at room temperature [2]. Since SIS and HEB mixers require 4 K cooling, operation at 20 K offers a major simplification of system design and a significant risk reduction for the submillimeter-wave instruments.

It is also important to note that the sensitivity to physical temperature is much less for amplifiers than SIS and HEB mixers. The amplifier-based receivers would still work at higher temperatures, though at a bit higher system noise, unlike the SIS and HEB receivers. Moreover, the higher operating temperature makes these amplifier receivers better suited to planetary instruments and earth remote sensing suborbital platforms where available power is scarce. In this paper, we discuss the science drivers and progress in the cryogenic HEMT amplifier based heterodyne receivers at submillimeter wavelengths and their potential for future spectroscopic and radiometric instruments.

II. Cryogenic Amplifier Based Receivers

In the last few years, the development of transistor technologies with f_{MAX} > 1 THz has pushed operating frequencies of amplifiers well into the 700 GHz range.

Northrop Grumman Aerospace Systems (NGAS) has developed an ultra-short-gate-length HEMT process which has produced InP HEMT amplifiers working at 700 GHz and beyond [1]. Fig. 1 shows photograph of such an amplifier chip along with its measured S-parameters. Availability of this technology opened up the opportunity to use amplifiers in a submillimeter-wave system for the first time.

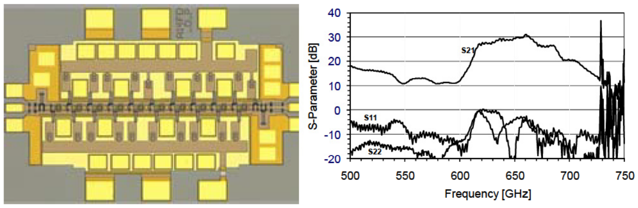

Fig. 1: Microphotograph of a Northrop Grumman 670 GHz 10-stage low noise amplifier (top) and its measured on-wafer S-Parameters (bottom) [1].

For many applications such as astrophysics, planetary, and Earth sciences, the sensitivity of the radiometer and spectrometer is the key driver, and hence the noise temperature of the amplifiers at submillimeter-wavelengths is an important parameter. HEMT-based MMIC amplifiers in the 150-180 GHz frequency band have been tested at room temperature as well as at 30 K, and their noise performance has been characterized as a function of temperature [3]. Recently, a W-band amplifier cooled to 20 K measured 27 K noise temperature [2] – almost a factor of ten improvements from its room temperature performance. Moreover, a three-stage HEMT amplifier with integrated HEMT-based subharmonic mixer operating at 165 GHz was also tested at room temperature as well as at 21 K. At 21 K, the measured system noise temperature was almost 50 K.

We evaluated a 10-stage HEMT amplifier in a waveguide block in our laboratory. When measured at room temperature, the amplifier showed a peak gain of more than 20 dB and 4500 K noise temperature. The amplifier was measured in a cryostat which can be cooled to 20 K and has a mechanical chopper for automated measurements, as shown in Fig. 2. When cooled to 20 K, the measured noise temperature of the amplifier improved by more than a factor of seven. Fig. 3 shows the measured performance of the amplifier at different temperatures. InP HEMT based mixers and multipliers have also been designed and tested in this frequency band. An integrated compact and low power MMIC chip containing an LNA, mixer, and frequency multiplier has been designed and tested at 670 GHz and was found to perform well at room temperature [4]. We are in the process of evaluating the integrated receiver at cryogenic temperatures.

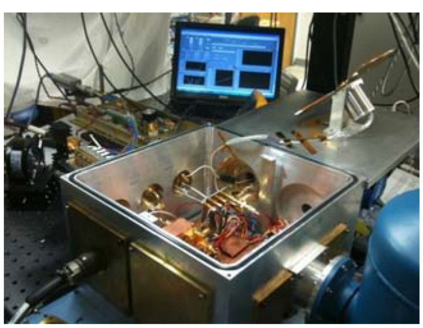

Fig. 2: Cryogenic test set-up with mechanical chopper for measuring HEMT amplifiers and receivers at 20 K.

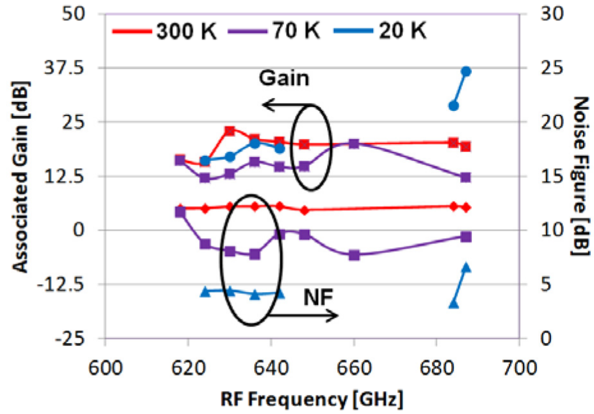

Fig. 2: Performance of 650 GHz HEMT based amplifiers at various operating temperatures.

III. CONCLUSION

InP HEMT based amplifiers at submillimeter wavelengths have shown a factor of seven to ten improvements in noise temperature performance when cooled to 20 K compared to their room temperature performance. This makes it feasible to use them in future astrophysics, planetary science, and Earth science instruments which currently use SIS based mixers. Since SIS mixers require 4 K cooling, amplifiers cooled to 20 K offers an alternative to the power hungry 4 K systems without paying much of a penalty in performance.

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